

Hole Transportation in Photocells Based on Hydrogenated Amorphous Silicon

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ABSTRACT

In this manuscript, amorphous hydrogenated silicon films were studied by using the photo-CVC vidicon target characteristics. In the photo-CVC characteristic, a region is observed that obeys the quadratic law. It is explained that the changes contribution in the a -Si:H dielectric constant and the hole lifetime depending on the applied voltage for obtaining information from this section about the hole transportation mechanism is too significant.

KEYWORDS: amorphous semiconductor, hydrogenated silicon, vidicon target, hole traps, traps energy, mobility gap, sticking centers

INTRODUCTION

At present, the photovoltaic devices quality and efficiency, including solar cells based on amorphous hydrogenated silicon a -Si:H, cannot sufficiently meet the requirements for semiconductor photo converters. The solar cells efficiency based on a -Si:H under standard conditions (AM spectrum $1.5 - 1000 \text{ W/m}^2$) reached 8-10% [1], and for tandem structures, calculations show that it is possible to achieve up to 12-15% and more [2].

It is known that the photocurrent in solar cells consists of two components, that is, electron and hole. The difference in the mobility value of these components is very significant ($\mu_e = 13 \text{ cm}^2/\text{W}\cdot\text{s}$ and $\mu_n = 0,67 \text{ cm}^2/\text{W}\cdot\text{s}$). This means that hole photocurrent fraction in the photocurrent is insignificant.

Therefore, in many works to study the transfer mechanism, the electron dependences and hole photoconductivity of a -Si:H и a -Si:H(B) samples on temperature and it was found that in high-quality a -Si:H samples, the electrons photoconductivity depends very little on temperature, and in lightly boron-doped a -Si:H samples, the holes photoconductivity depended on the temperature at which the stationary photoconductivity was measured in planar samples [3].

To analyze the solar cells characteristics and find ways to further increase their photo conversion efficiency requires a detailed fraction study of each current carriers type and to establish their transfer mechanism.

This work is devoted to the theoretical study of the current-voltage characteristic (CVC) of hole photocurrent and shows the obtaining information possibility from individual photo-CVC sections about hole transfer mechanism.

The vidicon target photo-CVC analysis and calculation.

To study the hole transfer mechanism in the photocurrent structures based on a -Si:H, it is necessary to have a monopolar photocurrent, in which only photo generated holes are current carriers. We will consider a structure, that is, the vidicon target structure (Fig.1a.), in which all layers consist of a -Si:H.

If illumination is produced from the n layer side by light with $\lambda \sim 400 \text{ nm}$ wavelength, then the light is absorbed at the i -layer surface and a carriers "reservoir" or a layer enriched with holes is formed in this i -layer part.

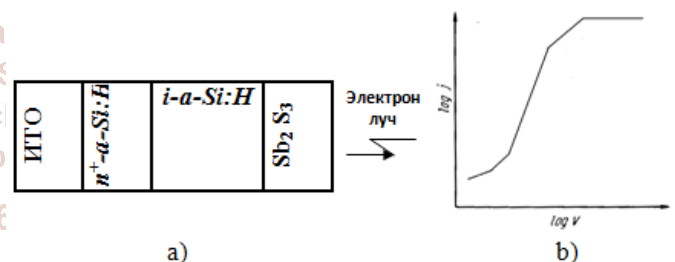


Fig.1. The vidicon target (a) structure and the vidicon target ideal photo-CVC (b).

When a reverse voltage is applied, only holes are current carriers. This phenomenon was discovered when measuring the photoconductivity by the vidicon method [4].

It is known from the studies' results of such photo-volt-ampere characteristics structures that photo-CVC consists of several sections [8].

This photo-CVC behavior can be explained as follows: suppose that at low temperatures the entire space charge is formed by photo generated mobile holes in the valence band, then the transfer phenomena can be represented as follows. Hole traps create deep energy levels, so that the reverse holes thermal ejection can be neglected, moreover, the traps are evenly distributed over the volume. The traps concentration is much higher than the equilibrium holes concentration in the i -layer, which confirms the low value of the dark current. Then, at low voltages, almost all injected photo generated holes are captured by traps, so the hole concentration in the i -layer depth will not increase. This position corresponds to the ohmic region in the photo-CVC obtained at low temperatures. With increasing voltage, all

traps are filled with injected holes and the hole concentration begins to grow.

At some voltages, the injected holes concentration is much higher than that deep traps. This will happen if the photo generated holes concentration is greater than the traps concentration. If these conditions are satisfied, then for this case we have the following equations:

For current density

$$j = ep\mu_p E + D\nabla p \quad (1)$$

For the electric field distribution in the *i-a-Si: H* region, we have Poisson equations

$$\frac{\partial E}{\partial x} = \frac{4\pi e}{\varepsilon} (p + N(f - 1)) \quad (2)$$

and the equation for the charge exchange kinetics

$$N \frac{\partial f}{\partial t} = \frac{\Delta p}{\tau_p} - (f - 1) \frac{\Delta N}{\tau_n} - g \quad (3)$$

Here N is the hole traps concentration in the mobility gap, X is the concentration of injected photo generated holes, τ_p is their lifetime, μ_p is the hole mobility, g is the thermal generation rate of the *i*-regions majority carriers, f is the filling factor of hole traps, and this value at thermodynamic equilibrium is determined by the following expression:

$$f = \frac{1}{1 + \frac{N_d}{G\tau}}$$

Here G is the photogeneration rate.

To solve these equations, we will evaluate some terms of these equations. Due to the diffusion smallness coefficient, we neglect the second terms (1) of the equation. Due to the dark current dependence on voltage [5], it can be seen that g thermal generation is insignificant, so we will not take it into account. The quantities ΔN , Δp , ε and f depend on the applied voltage. As the voltage increases, the injected holes number in the *i*-layer increases strongly and all traps become filled, as mentioned above, then the filling factor is $f = 1$ if thermodynamic equilibrium occurs between the traps and injected holes. Then the following condition is satisfied:

$\frac{\partial f}{\partial t} = 0$ и $p \gg N$, taking into account the above-given conditions

from equation (3) we have $\frac{\Delta p}{\tau_p} = 0 \Rightarrow \Delta p = 0$ or $p = \text{const}$ then the equation (1) and (2) takes on the following:

$$j = ep\mu_p E \quad (4)$$

$$\frac{\partial E}{\partial x} = \frac{4\pi e}{\varepsilon} \cdot p \quad (5)$$

Solving together (4) and (5) the equation we have the following expression for the relationship between

E и j $\frac{\mu_p \varepsilon E}{4\pi} \partial E = j \partial x$. To integrate this expression, it is necessary to estimate the lower integral bounds. As is known, in the vidicon mode, the incident light is absorbed at the *i*-layer surface to x_0 depth. This thickness, in which the holes are photogenerated, can be called a "virtual" cathode.

With an increase in the external stress, this section expands, but at lower stresses, we can assume $x \ll L$, L is the *i*-layer thickness, therefore we will integrate from 0 to L .

Considering the above conditions, we get the relationship between the applied voltage current.

$$j = \frac{\mu_p \varepsilon}{8\pi} \cdot \frac{U^2}{L^3} \quad (6)$$

Thus, we got the Mott's quadratic law. As seen from (6), the photocurrent value depends only on the hole parameters. Therefore, information on the hole transfer mechanism can be obtained. To show this expression reliability and applicability for the Vidicon photo-CVC target, we will analyze the experimentally obtained graphs and carry out a numerical calculation. In [6], photo-CVCs were obtained at different temperatures (Fig. 2).

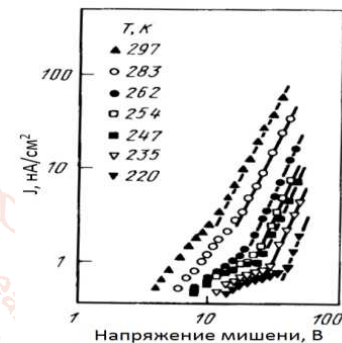


Fig.2. Photo-CVC obtained at various temperatures.

As can be seen in the temperature dependence, the photo-CVC section, which obeys the "quadratic" law, is shifted almost parallel to the high voltage region. This photo-CVC behavior for samples with different thicknesses satisfies (6) equation. The holes' photoelectric parameters depend on temperature, therefore, from this section of the photo-CVC, it is possible to obtain the temperature dependence of the holes' photoelectric parameters. And this case requires additional research. To determine the holes' photo generation rate, we used the following expressions.

Where $I_0^{p(s)}$ is the incident light spectral density, $\alpha_i(\lambda)$ is the incident light coefficient in the *i-a-Si: H* layer, T_{ni} is the n layer transmittance into the *i*-layer, p and s are polarization indices, to obtain a photo-CVC plot obeying the "quadratic law", we will use the following values and estimates of some parameters of *i-a-Si: H*.

When measuring the vidicon target photoconductivity, the light falls normally and is completely absorbed in the *i*-layer, in addition, the n -layer thickness is insignificantly relative to

the *i*-layer. Then $R_{pi}=0$, a $T = \frac{n_{in}}{(n_{ni} + 1)^2}$ Where n_{in} is the relative refractive index. If we take into account that the n and *i*-layer consists only of *a-Si: H* then $n_{in} \approx n_{ni} = 1$ and $T=1$. The coefficient values of defect absorption $\alpha(\lambda) \sim 1-10 \text{ cm}^{-1}$, the holes mobility $\mu_p = 0.67 \text{ cm}^2/(\text{B}\cdot\text{c})$, $m=34\div35$ and $d \approx 1 \mu\text{m}$. When light is absorbed at the surface *i*-layer, as indicated above, a carriers "reservoir", that is, holes, appears, and along with it, a potential difference appears between the *i*-layer part that absorbed and not absorbed light. Photo generated holes must overcome this potential barrier. The

potential barrier height depends on the energy distribution width of the defects state density near the Fermi level. As is known, the defects state density near the Fermi level is several orders of magnitude lower than the state density in the rest of the mobility gap. Therefore, when the incident light is absorbed at these levels, all the electrons in these states pass into the conduction band and due to this, the Fermi level shifts downward. The distribution of these states obeys the Gaussian law [7].

$$N(E) = (2\pi\sigma^2)^{-\frac{1}{2}} \exp\left(-\frac{(E - E_0)^2}{2\sigma^2}\right)$$

Here E_0 is the state density peak of the Gaussian distribution; σ is the energy width of this distribution. Given the above data, it can be assumed that the potential barrier height is comparable to that value.

When the $\Delta\varphi = U$ condition is fulfilled, all photo generated holes are injected into the entire i -layer without obstruction. And then the two conditions $p \gg N$ and $p = \text{const}$ are fulfilled, therefore, the section that obeys the quadratic law begins with this voltage.

If the total photo generated holes concentration is less than the defects concentration, that is, $p < N$, the area that obeys the "quadratic" law is not observed. This is evidenced by the obtained photo-CVC at low illumination or samples with a high defects concentration [4,8]. Thus, we will be able to determine the voltage at which the "quadratic" section begins.

Since in $a\text{-Si:H}$ samples lightly doped with boron, hole traps are the main trapping centers for non equilibrium holes [4]. In this case, the hole lifetime τ_p is determined by hole traps

concentration N_d , N_d , $\tau_p = (C_p^0 \cdot N^0)^{-1}$ Here C_p^0 is hole capture ratio.

With the holes injection with a higher concentration, that is, $p > N^0$, with increasing voltages, hole traps gradually capture more holes. This leads to these traps recharge, as a result of which the hole traps concentration decreases. Accordingly, the hole lifetime increases and, as a consequence, an additional increase in the photocurrent should occur.

At high voltages, the entire i -layer is filled with injected holes with an almost constant volume concentration p , which means that the photocurrent does not obey the quadratic law.

This voltage can be estimated by equating the hole transfer time to the i -layer thickness with the Maxwell relaxation time, from this voltage the ohmic section or saturation current begins. Comparing the hole transfer time with the Maxwell relaxation time, we can estimate the stress in which the quadratic section ends.

Obtained results discussion and their comparison by experiments

To compare the theory with experimental data, let us use the results of [4], in which $a\text{-Si:H}$ samples with different parameters and under different illumination were studied by the vidicon method.

In [4], the measurement was carried out on the same type sample, but at different illumination powers. As can be seen, with decreasing illumination power, the number of photo generated holes decreases, when the concentration of photo generated holes goes down below the $p = N_d$ boundary, the quadratic section is not observed. This is also an additional proof of our assumption.

From the experimental plots obtained in [8], it can be seen that no other photocurrent dependences on the applied voltage were observed before the quadratic beginning section. That is, when voltage is applied, a section begins, which obeys a quadratic law. This photo-CVC behavior can be explained by low value of the defect concentration in the mobility gap. In [4], $a\text{-Si:H}$ samples were investigated by the vidicon method at different temperatures [Fig. 2]. Different sections of the photocurrent can be distinguished from the graph depending on temperatures. The calculated data of the vidicon photo-CVC target according to formula (6) with some photoelectric parameters dependence use on the applied voltage and without it is shown in Fig. 3.

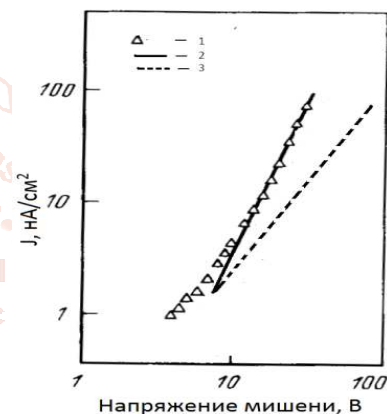


Fig.3. Experimental (1) and calculated (2,3) vidicon photo-CVC target. (2) - taking into account the change in ϵ and τ from the applied voltage, (3) - obtained without taking into account the change in ϵ and τ

As you can see, if we take into account the above-said dependences, then the calculated photo-CVC are in good agreement with the experimental data. A decrease in the photocurrent at low temperatures can be explained as follows: a decrease in temperature reduces the holes thermal ejection probability from trap states into the valence band. In addition, the potential barrier value also depends on temperature; therefore, the photo-CVC behavior at low temperatures requires additional research.

Conclusion

Based on the above, we can conclude that on the quadratic section of the photo-CVC vidicon target based on $a\text{-Si:H}$, the photocurrent not only depends on the applied voltage directly, but it is necessary to take into account changes in the dielectric constant of the $ia\text{-Si:H}$ layer, the lifetime holes τ from the applied voltage. Thus, it is impossible to obtain reliable information on the hole mobility from equation (6). To determine the hole mobility, it is necessary to take into account the changes in the dielectric constant of the sample under the influence of an external voltage. As mentioned above, with a change in the distribution of injected holes, the lifetime increases and, in turn, the transfer of holes decreases. Therefore, these changes are also appropriate to take into account.

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